NOTE ON THE SEMI-ANNUAL WIND VARIATION IN THE EQUATORIAL STRATOSPHERE

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ABSTRACT

Rocket wind soundings for several stations within 10° latitude of the equator are used to analyze details of the structure of the recently discovered semi-annual wind variation in the equatorial upper stratosphere. The cycle is characterized by winter and summer easterlies and equinoctial westerlies and in 1966 appeared to have maximum amplitude at 45–50 km. Its global extent is confirmed with the aid of rocket data from widely separated longitudes. The semi-annual variation is discussed in relation to the quasi-biennial oscillation, which has maximum amplitude in the lower stratosphere. A possible explanation of the origin of the semi-annual variation is mentioned and attention is called to semi-annual variations in other parameters in the upper atmosphere.

1. INTRODUCTION

In recent years, the tropical atmosphere below about 30 km. has received considerable attention (e.g., Angell and Korshover [1]; Reed [10]), primarily because of evidence of cyclic variations in the stratospheric wind, temperature, and ozone. Analysis above this level, however, has been hampered by the sparsity of observational data. Reed [11], on the basis of rocket observations for Ascension Island (07°59′ S., 14°25′ W.), has demonstrated that while the quasi-biennial oscillation in the zonal wind predominates at the lower levels, a semi-annual component increases in relative magnitude at the higher levels. An annual component in the circulation appears to be present at all altitudes of the stratosphere and mesosphere.

The semi-annual variation was first alluded to briefly by Webb [17] and Reed [10, 11] on the basis of data from Ascension Island alone. Subsequently, Reed [12] made a thorough analysis based on data from two stations at widely separated latitudes, Ascension Island and Barking Sands, Hawaii (22° N., 160° W.).

A marked improvement in the observational coverage occurred in 1966, following the establishment of meteorological rocket stations at Natal, Brazil (05°45′ S., 35°10′ W.) and Fort Sherman, Panama (09°22′ N., 79°54′ W.). The station at Natal began operating in January 1966 under the auspices of the Experimental Inter-American Meteorological Rocket Network (EXAMETNET), and the station at Fort Sherman was inaugurated in March 1966, as a member of the (North American) Meteorological Rocket Network. The data from these stations, together with rocket observations from Ascension Island and Thumba, India (08°32′ N., 76°52′ E.) provide the first opportunity to study the structure of the semi-annual variation at different longitudes north and south of the equator, without the need of assuming hemispheric symmetry.

The purpose of this note is to describe our findings concerning the semi-annual variation of the wind, based on rocket observations for the stations mentioned above. The main discussion will be preceded by an examination of the phase of the biennial oscillation up to the period of analysis.

2. PHASE OF THE QUASI-BIENNIAL CYCLE

Reed [11] has shown that the quasi-biennial oscillation in the zonal wind persists into the middle and upper stratosphere. As our data are concentrated mainly in 1 year, it is helpful to determine the phase of this phenomenon during the period of investigation. Figure 1 presents the monthly mean values of the 10-mb. (~30-km.) zonal wind component from January 1958 through August 1966 at Balboa, Panama (08°56′ N., 79°34′ W.) and Ascension Island. These data were kindly provided to the authors by Julius Korshover, Air Resources Laboratory (ESSA). The data from November 1965 at Ascension and from September 1966 at Balboa are considered preliminary, though reasonable, values.

Although the results are somewhat complex, it is apparent that the zonal wind reached its westerly maximum in early 1966, with a return to easterlies by June at both stations. The relative weakness of the westerlies, compared to the easterlies, is a feature noted by Reed [10]. Examination of the peaks at Balboa and Ascension suggests that the westerlies at the former station tend to precede those at Ascension by 4–6 months. One might

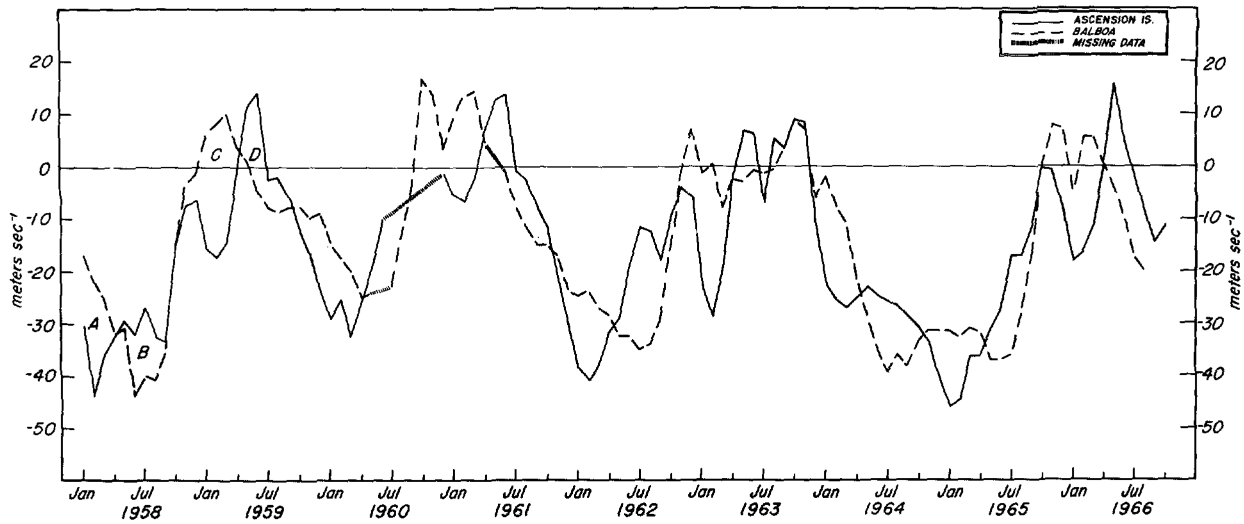


FIGURE 1.—Monthly averaged zonal winds (m. sec.$^{-1}$) at 10 mb. for Balboa, C.Z., and Ascension Island. Positive winds are from the west.

thus speculate that the biennial oscillation is not independent of longitude. Closer examination, however, indicates that the lag in the westerlies is merely an effect of the annual cycle in the circulation, whose amplitude has been estimated by Reed [12] to be 5–10 m. sec.$^{-1}$ for Ascension, at 30 km. Around January (see, for example, area A of fig. 1), the dominant westerlies of the Northern Hemisphere winter influence the low-latitude station at Balboa, which consequently records weaker easterlies than Ascension, the latter station being under the influence of the Southern Hemisphere summer easterlies in that time of year. In April, soon after the vernal equinox, the situation is reversed, so that by June (area B) the easterlies are stronger at Balboa than at Ascension. A similar analysis applies to areas C and D and to all major troughs and peaks in the figure.

Essentially this form of wave interference was noted at 50 mb. by Belmont and Dartt [5] in describing latitudinal shifts of the zonal wind maxima about the equator. The minimum under area C (February 1959) and in corresponding epochs of the other biennial cycles is associated with the enhanced easterlies of the Southern Hemisphere summer. The Balboa and Ascension curves systematically cross near the equinoxes, when the annual component should be close to zero. Intuitively, therefore, one would expect to eliminate the annual component by tracing a curve approximately half-way between the Balboa and Ascension curves, passing through the points of intersections. Such a curve would then essentially represent the biennial oscillation. The validity of this argument was tested by eliminating the annual component by constructing a curve based on 12-month running means. The curve obtained agreed fairly well with the curve traced in the manner described above.

A complicating feature, however, is the presence of a semi-annual cycle, resulting in the addition of an easterly component in winter and summer at both stations.

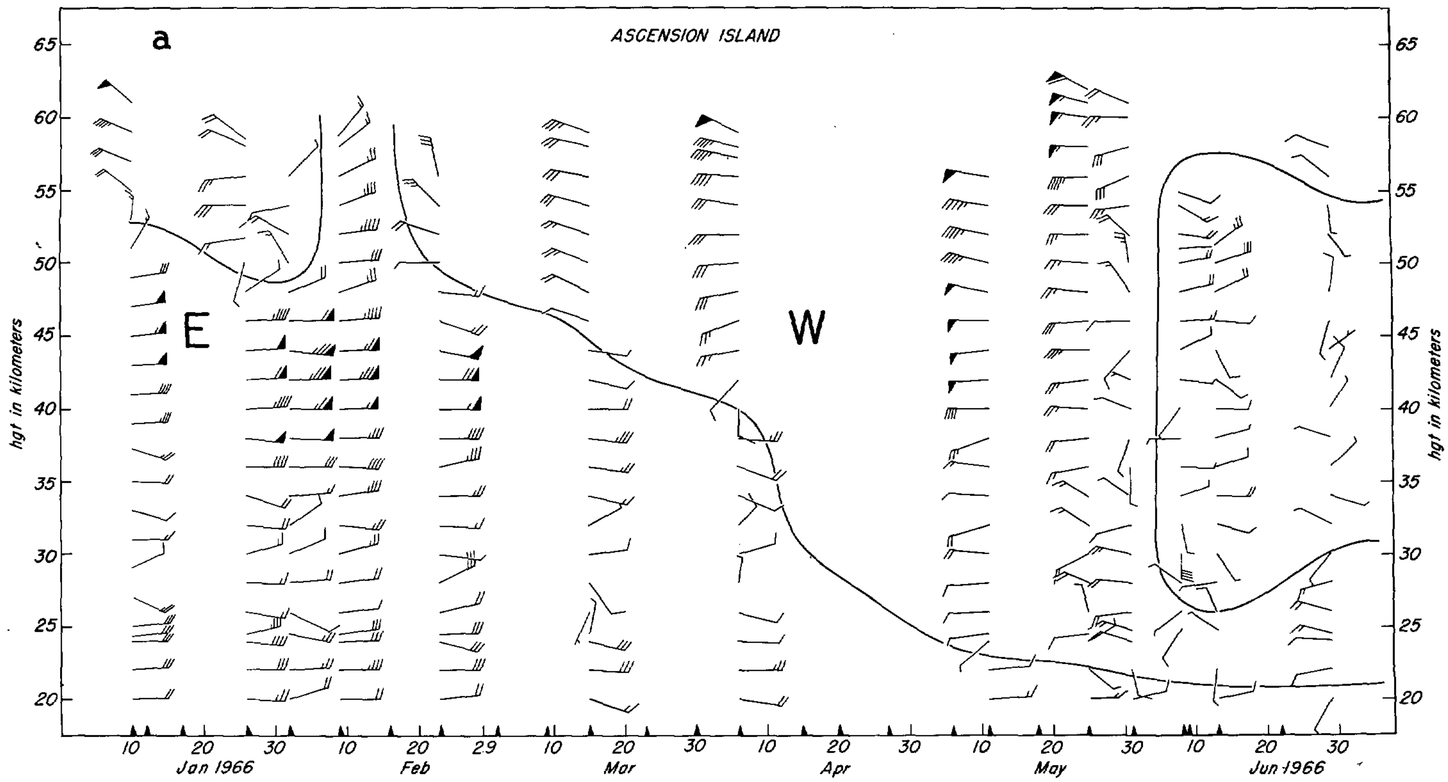
The foregoing discussion, aside from defining the phase of the biennial oscillation in 1966, points up the importance of isolating the annual cycle in comparisons of data north and south of the equator. The relevance of this problem to the semi-annual oscillation will be seen in the next section.

3. INTER-HEMISPHERIC COMPARISON AT HEIGHTS 30 TO 60 KM.

Figures 2, 3, and 4 are time sections drawn from vector winds for observations taken at approximately weekly intervals, indicated by arrows at the base of the figures. To avoid overcrowding of the figures, only selected wind soundings are shown to illustrate features of interest. Although harmonic analysis of zonal winds would prove helpful, especially when longer coinciding periods of observation become available for the equatorial stations, the unmodified resultant wind field itself merits examination. Some ingenuity, and not a little imagination, are required, however, to unmesh the annual, semiannual, and quasi-biennial components of the circulation.

The main pattern that emerges is a cycle characterized by easterly winds during the winter and summer and westerlies around the time of the equinoxes. Figures 2–4 and rocket data for Thumba, India (8° N.) [2] indicate that the cycle is of global extent at equatorial latitudes. The variation is detectable in higher latitudes, for example, at Antigua, B.W.I. (17° N.) and at Barking Sands (22° N.), and it is apparent that, as with the biennial oscillation, its amplitude diminishes with increasing latitude.

Careful examination of figures 2–4 reveals the following features:



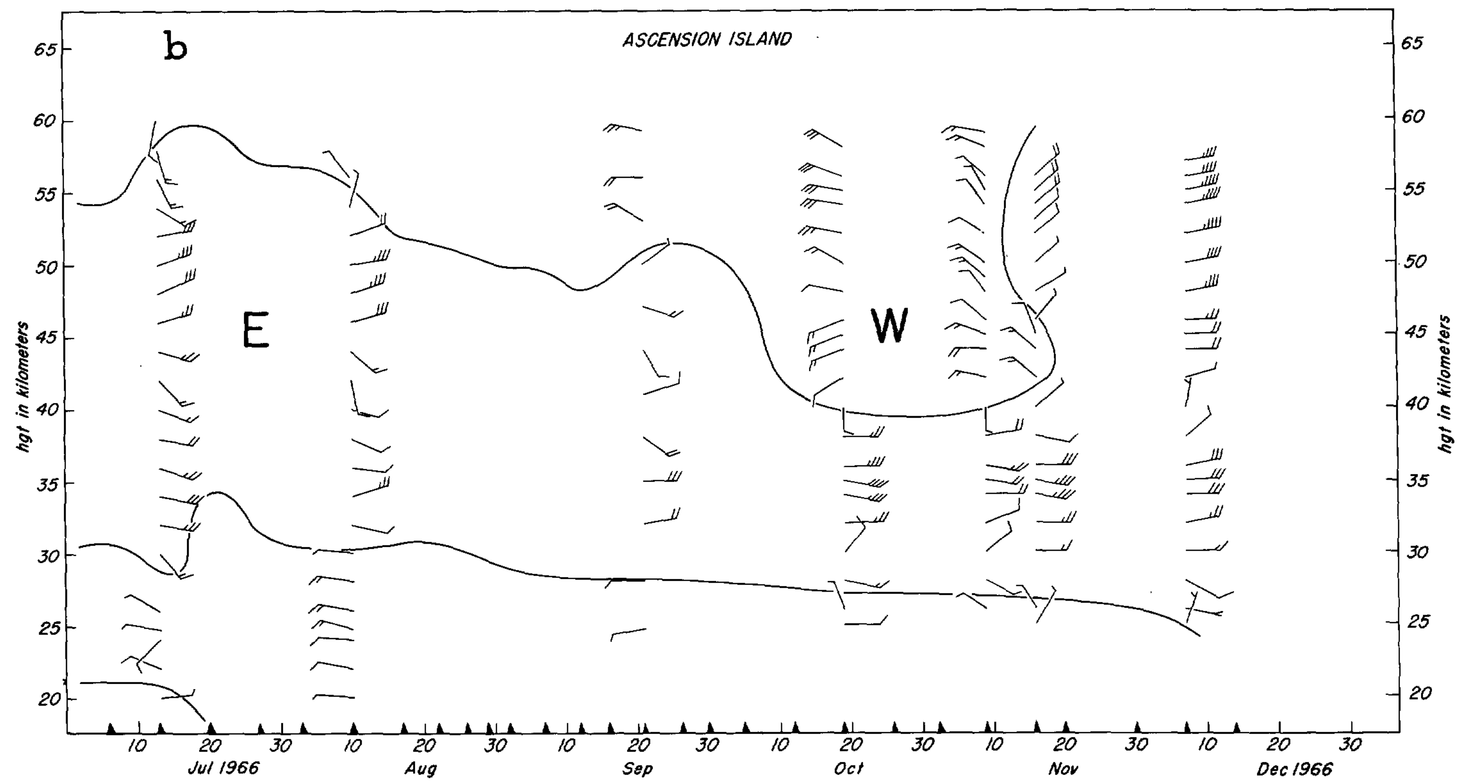


FIGURE 2.—Time section of observed rocketsonde winds (m. sec.$^{-1}$) for Ascension Island: (a) January-June 1966; (b) July-December 1966. The heavy black lines generally separate winds with easterly components from those with westerly components. Indentations from bottom scale indicate all days for which observational data were used. A full barb represents 10 m. sec.$^{-1}$; a pennant, 50 m. sec.$^{-1}$

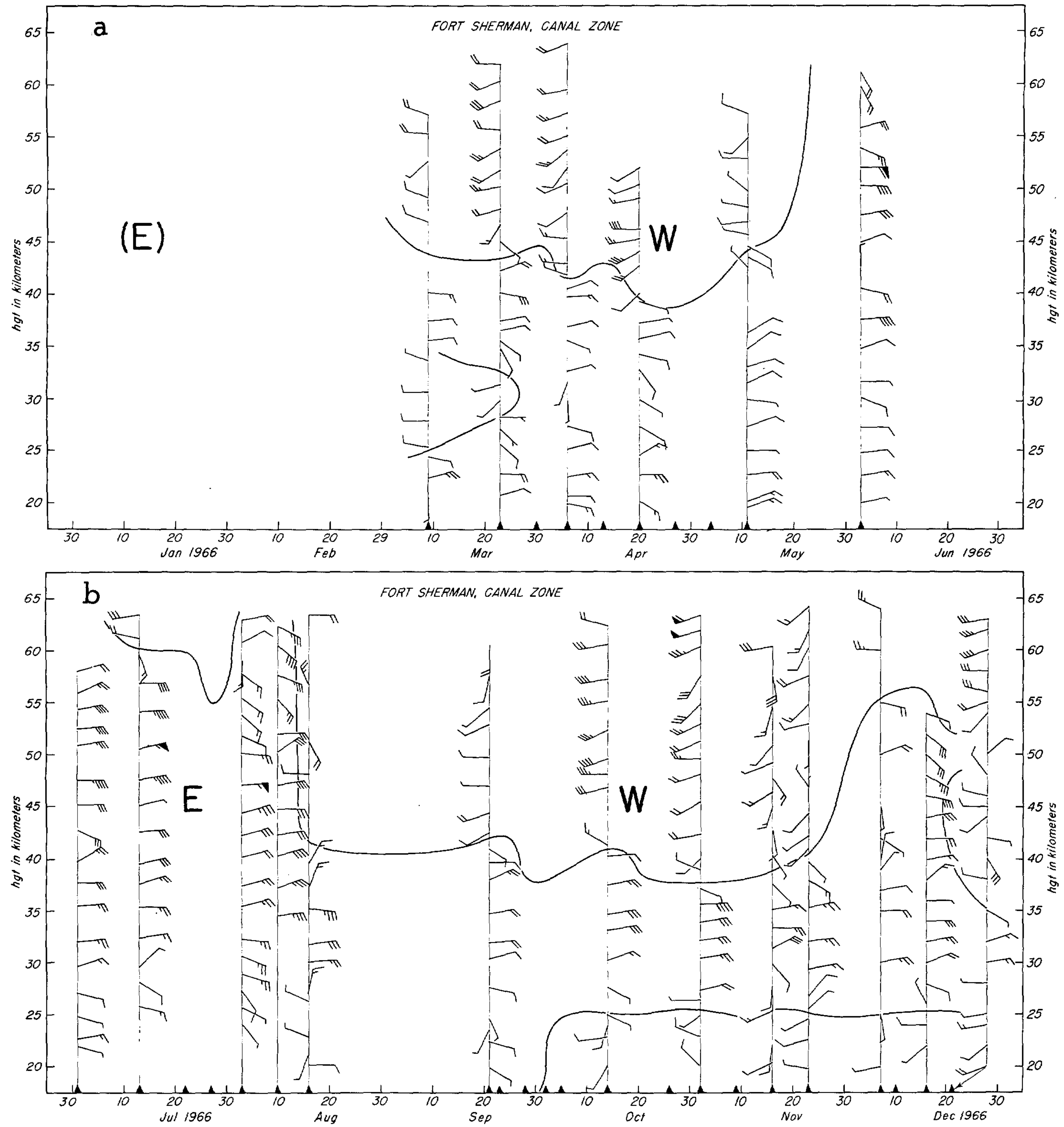
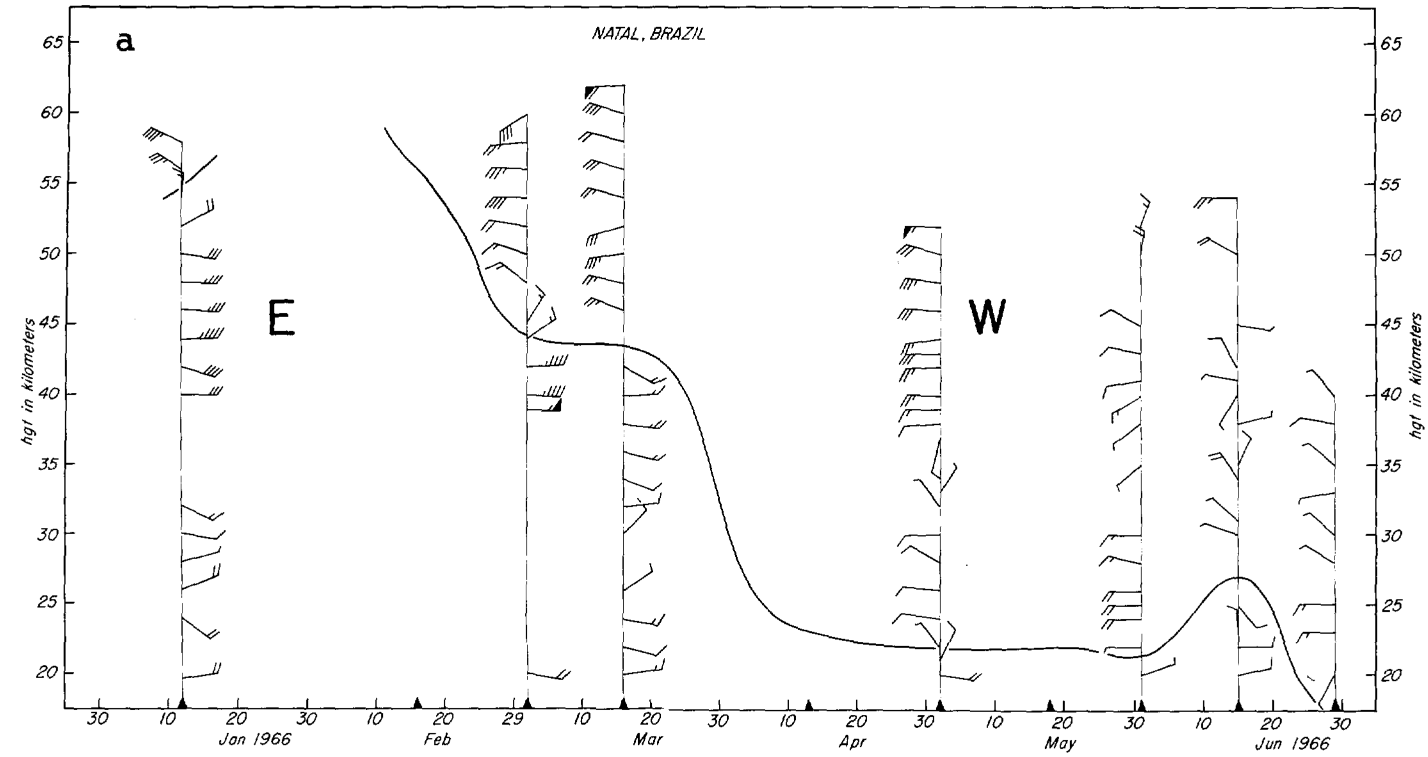


FIGURE 3.—Time section of observed rocketsonde winds for Fort Sherman, C.Z.: (a) March-June 1966; (b) July-December 1966. Explanation as in figure 2.



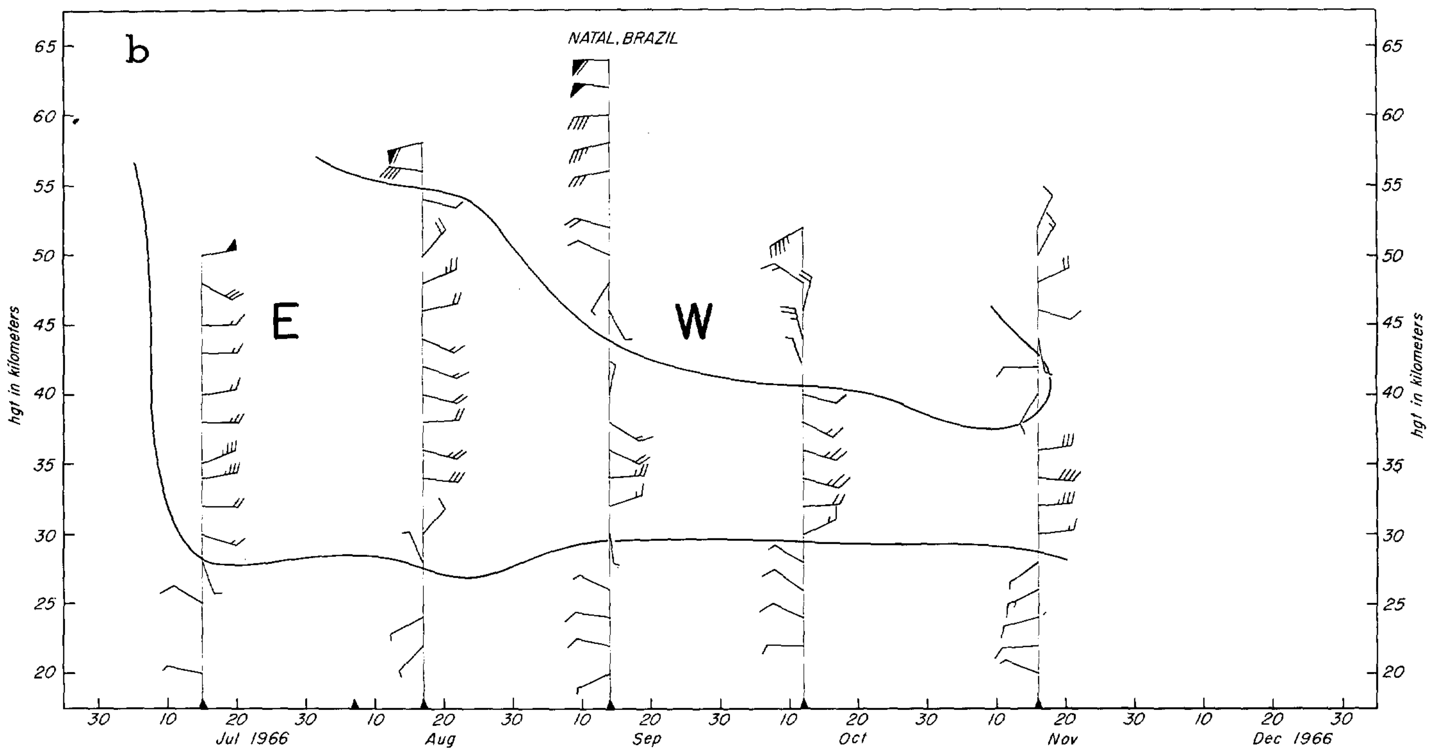


FIGURE 4.—Time section of observed rocketsonde winds for Natal, Brazil: (a) January-June 1966; (b) July-November 1966. Explanation as in figure 2.

(a) The transition from westerlies to easterlies may occur rather suddenly throughout a deep layer centered at about 45 km. In contrast, the transition from easterlies to westerlies proceeds downward and somewhat irregularly, at the rate of about 5–10 km./month.

(b) When the semi-annual easterlies coincide with the summer hemispheric easterlies of the mesosphere, a deep column of easterlies is expected. When they occur together with the winter hemispheric westerlies of the mesosphere, a shrinking of the column of easterlies is expected. A notable exception to this pattern is seen for January 1966 at Ascension, when an anomalous intrusion of westerlies occurred above 50 km.

(c) The summer easterlies (June-Aug. at Fort Sherman, Dec.-Feb. at Ascension and Natal) appear stronger than the winter easterlies (see table 1), but this difference may be attributed to the influence of the annual circulation. The amplitude of the semi-annual variation seems to have a maximum at 45–50 km., but a statistically reliable evaluation is not possible from the short observational record available concurrently for these stations. For a harmonic estimate of the amplitude at Ascension Island, based on 2 yr. of data, see Reed [12].

The relationship between the semi-annual variation and the biennial oscillation, which has maximum amplitude in the lower stratosphere, is not immediately apparent. It will be remembered from the discussion of figure 1 that westerlies in the biennial oscillation were seen first at Fort Sherman (Balboa), as a result of interference (amplification) from the winter westerlies of the Northern Hemisphere. In figure 3a, only a residue of weak westerlies persists at Fort Sherman at 30 km., giving way to biennial easterlies at the end of March. At Ascension and Natal (figs. 2a, 4a), 30-km. westerlies are not seen until mid-April and have a brief duration, consistent with the pattern in figure 1. In figure 2a, the biennial westerlies of April-June appear as an integral part of the spring equinoctial westerly regime of the semi-annual oscillation. The data for Natal (fig. 4) and for Thumba, India, show similar behavior. In September-October, however, the equinoctial westerlies at any of the stations descend only to about 40 km., hence the presence of easterlies at 30 km. The observed pattern of westerlies, stronger in spring than in fall, thus may be due merely to the presence of biennial westerlies in the first half of 1966. Clearly, we must await more rocket information from the tropical regions before the interaction among the circulation components can be adequately understood.

TABLE 1.—*Approximate values of maximum observed zonal wind speed (m. sec.$^{-1}$) at 40–50 km., based on 1966 data unless otherwise noted*[1]

Station	Component			
	E	W	E	W
Ascension (8° S.)	75 Feb.	50 May	40 July	30 Oct.
Natal (6° S.)	50 Jan.-Mar.	50 May	40 July	45 Oct.
Fort Sherman (9° N.)	40 Dec.	40 Apr.	50–60 June-Aug.	40 Oct.
Thumba (9° N.)	40 Feb.	40 Apr.	50 July (1964)	35 Oct. (1965)

[1] First rocket observations at Fort Sherman: March 1966. For Thumba, data were not available subsequent to April 1966.

4. IMPLICATIONS OF LONGITUDINAL DIFFERENCES IN THE SEMI-ANNUAL VARIATION

No evidence of systematic longitudinal differences is apparent in the data presented. A net northward component at Fort Sherman and a southward component at Ascension and Natal are suggested by the data. However, the rocket observations at the three stations were taken mainly in daytime, and whether the meridional components are due wholly or in part to diurnal tidal effects, in the manner suggested by Reed, McKenzie, and Vyverberg [13] or by Webb [16], or are perhaps a reflection of cellular synoptic structure, is a question beyond the scope of this note.

A longitudinal effect is suggested, however, in the Natal-Ascension region by the data for June-July 1966. The easterly component of the semi-annual variation is seen in early June at Ascension, but at Natal it is not observed until a month later. At other times of the year there is considerable similarity in the pattern of these two stations, whose latitudes differ by only 2° with a longitudinal separation of 21°.

Such features as this and the observed lack of symmetry in the speed of the easterlies about the equator suggest that synoptic analyses of the equatorial region will be needed for a complete description of the stratospheric circulation.

5. POSSIBLE CAUSES OF THE SEMI-ANNUAL WIND VARIATION

The semi-annual variation of wind in the equatorial upper stratosphere can probably be explained as a consequence of the double passage of the sun over latitudes between 23.5°N. and S. A semi-annual variation of temperature in the upper stratosphere, detectable at least to 30°N., with maximum amplitude above 40 km., has been described by Batten [3, 4]. North-south temperature gradients implicit in this temperature model are roughly consistent, at least during certain times of the year, with observed vertical wind shears.

The main anticyclonic system of the summer hemisphere, centered near the pole, may in the simplest possible terms be considered to owe its existence to the long duration of sunlight in high latitudes, despite low solar elevation angles. A secondary maximum in the pressure field (i.e., a ridge) may be envisioned migrating seasonally about the equator, associated with a high solar elevation angle. A spillover of easterly winds equatorward of this ridge into the opposite hemisphere is required to explain the presence of easterlies on both sides of the equator, in both summer and winter. Still another ridge-like formation is required separating the overflowing easterlies and the winter hemispheric westerlies. (It is this feature that possibly explains the aforementioned June-July variation between Natal and Ascension.) At times when the annual component of the circulation is especially strong, and also at altitudes of a pronounced biennial component, a distortion of the ideal configuration sketched above would be expected.

Finally, it is pertinent to note the presence of semi-annual variations in the mesosphere and above, as exhibited in (1) the circulation in the vicinity of the mesopause (Kochanski [7]); (2) the electron density in the D-region (Lauter and Sprenger [8]); (3) temperature and density in the thermosphere, with the semi-annual variation of density reaching maximum amplitude around 500 km., according to certain diffusion models (Jacchia [6]); and (4) the earth's magnetic field (e.g., Shapiro and Ward [15]). It is not the intent here to suggest a common factor influencing the variations mentioned above, but merely to call attention to their existence; the causes of the variations in the middle and upper atmosphere may be quite different. A complicated phase structure with respect to height is likely. The data presented by Kochanski indicate easterly winds around April and October, westerlies in January and August (Northern Hemisphere), opposite in phase with the semi-annual variation described in this note. In the upper thermosphere, the temperature and density have *maxima* in April and October, minima in January and July, in phase with the variation of the planetary geomagnetic index K_p (Jacchia [6]). Recent investigations, e.g., Newell [9], point to the possibility that certain variations in the high atmosphere may occur in response to variations in the stratosphere. Extensive and intensive research will doubtless be needed to clarify suspected relationships.

ACKNOWLEDGMENTS

This work was performed with the support of the National Aeronautics and Space Administration, under its EXAMETNET Program. We gratefully acknowledge the use of Natal rocket data provided by Brazilian EXAMETNET scientists in published form (Salgado et al. [14]) and in the form of original observations transmitted by Wallops Station, Va. Technical assistance was provided by L. P. Mannello and J. A. Booth.

REFERENCES

1. J. K. Angell and J. Korshover, "Quasi-Biennial Variations in Temperature, Total Ozone, and Tropopause Height," *Journal of the Atmospheric Sciences*, vol. 21, No. 5, Sept. 1954, pp. 479–492.
2. Anonymous, "Indian Rocketsonde Data," *Indian Journal of Meteorology and Geophysics*, vol. 17, No. 2, Apr. 1966, p. 317–318; vol. 17, No. 3, July 1966, p. 508.
3. E. S. Batten, "A Model of the Annual Temperature Variations at 30° N. and 60° N. Between 30 and 50 Km.," *Memorandum* RM–3564–PR, RAND Corporation, 1963, 32 pp.
4. E. S. Batten, "A Model of the Seasonal and Latitudinal Variation of Zonal Winds and Temperatures in the Stratosphere above 30 Km.," *Memorandum* RM–4144–PR, RAND Corporation, 1964, 28 pp.
5. A. D. Belmont and D. G. Dartt, "The Non-Repeating Variations of the Observed Wind in the Equatorial Stratosphere," *Tellus*, vol. 18, No. 2, May 1966, pp. 318–390.
6. L. G. Jacchia, "Static Diffusion Models of the Upper Atmosphere With Empirical Temperature Profiles," *Special Report* 184, Smithsonian Astrophysical Observatory, Cambridge, Mass., 1964.
7. A. Kochanski, "Circulation and Temperature at 70 to 100 Kilometers Height," *Journal of Geophysical Research*, vol. 68, No. 1, Jan. 1963, pp. 213–226.
8. E. A. Lauter and K. Sprenger, "D-Region Phenomena and Stratospheric-Mesospheric Coupling," *Bulletin of the American Meteorological Society*, vol. 48, No. 3, Mar. 1967, p. 216.
9. R. E. Newell, "Thermospheric Energetics and a Possible Explanation of Some Observations of Geomagnetic Disturbances and Radio Aurorae," *Nature*, vol. 211, No. 5050, Aug. 1966, pp. 700–703.
10. R. J. Reed, "The Present Status of the 26-Month Oscillation," *Bulletin of the American Meteorological Society*, vol. 46, No. 7, July 1965, pp. 374–385.
11. R. J. Reed, "The Quasi-Biennial Oscillation in the Atmosphere between 30 and 50 Km. Over Ascension Island," *Journal of the Atmospheric Sciences*, vol. 22, No. 3, May 1965, pp. 331–333.
12. R. J. Reed, "Zonal Wind Behavior in the Equatorial Stratosphere and Lower Mesosphere," *Journal of Geophysical Research*, vol. 71, No. 18, Sept. 1966, pp. 4223–4233.
13. R. J. Reed, D. J. McKenzie, and J. C. Vyverberg, "Diurnal Tidal Motions Between 30 and 60 Kilometers in Summer," *Journal of the Atmospheric Sciences*, vol. 23, No. 4, July 1966, pp. 416–423.
14. J. A. M. Salgado, U. Belculfiné, M. del Tedesco, and F. de Mendonça, "Meteorological Sounding Rocket Program at Natal," Laboratório de Física Espacial (São Paulo, Brasil), Report LAFE–47.
15. R. Shapiro and F. W. Ward, Jr., "Daily Normals of the International Magnetic Character Figure, C_i," *Journal of Geophysical Research*, vol. 65, No. 1, Jan. 1960, pp. 115–118.
16. W. L. Webb, "Stratospheric Solar Response," *Journal of the Atmospheric Sciences*, vol. 21, No. 6, Nov. 1964, pp. 582–591.
17. W. L. Webb, *Structure of the Stratosphere and Mesosphere*, Academic Press, New York, 1966, 382 pp.

[Received June 14, 1967; revised June 23, 1967]